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Ice/Hull Friction Coefficient Study

Summary Report

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ICE/HULL FRICTION COEFFICIENT STUDY

- SUMMARY REPORT -

For

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17. Abstract

This report documents a research project on ice/hull friction which a) reviews the different methods of hull surface roughness measurement, b) reviews the current methodology of hull surface representation and simulation at model scale, c) summarises the influence of each ice/hull interaction variable on friction coefficient, d) conducts a series of ice sample friction tests against carefully prepared reproductions of model surfaces, and e) conducts a series of level ice resistance model tests for three friction coefficients on the parallel midbody and bow of the M.V. ARCTIC.

The results of the work indicated that there were a number of factors which will influence the effective friction coefficient between the ice and the hull, and that the ice/hull friction is not Coloumb. The model tests, which were conducted with nominal friction coefficients 0.004, 0.060 and 0.400, demonstrated that friction has a significant effect on the resistance of the model. However, the augment of resistance associated with higher friction coefficients on the bow and midbody was not additive, i.e. the total increased resistance for a combined rough midbody and bow was less than the resistance obtained by adding together the resistance increase measured by testing the rough midbody and rough bow separately.

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17. Résumé

Ce rapport concerne une recherche sur le frottement des glaces contre les coques de navires. L'auteur y décrit: a) différentes méthodes de mesure de la rugosité des coques de navires, b) passe en revue les méthodes actuelles de représentation de l'état de surface des coques et de simulation de leur comportement tribologique à échelle réduite, c) décrit le lien entre le coefficient de frottement mesuré et chacune des variables d'interaction glaces/coque, d) rapporte les résultats d'une série d'essais de frottement d'éprouvettes de glace sur des éléments représentant fidèlement l'état de surface des coques modélisés et, e) commente une série d'essais des résistances à l'avancement dans une glace uniforme, la maquette du N.M. Arctic utilisée présentant trois coefficients de frottement différents dans la section médiane de la coque et sur la proue.

Les résultats des travaux révèlent qu'un certain nombre de facteurs influencent le coefficient de frottement réel entre la glace et la coque d'un navire et que ce frottement n'est pas conforme au schéma de Coloumb. Les essais sur maquette réalisés à coefficients de frottements nominaux de 0,004, 0,060 et 0,400 ont montré que ce facteur influait considérablement sur la résistance à l'avancement. Cependant, les résultats révèlent que l'effet de l'augmentation du coefficient de frottement sur la proue et dans la partie médiane de la coque n'était pas cumulatif, c'est-à-dire que l'augmentation globale de résistance due à la rugosité augmentée des deux segments de coque considérés est inférieure à celle obtenue en additionnant les augmentations de résistance attribuables à la proue et à la section médiane de la coque prises séparément.

18. Mots-clés	19. Diffusion
N.M. Arctic, résistance de la glace, frottement, coque de navire, essai sur maquette.	Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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1. INTRODUCTION

From 1982 to 1984, Melville Shipping Ltd. (Melville) conducted an extensive model test programme associated with the bow redesign of the Arctic Class bulk carrier M.V. ARCTIC. The test programme involved two bows, the ship's original bow and a new bow designed by Melville. The ship was refitted with the new bow, known as the 'Melville' bow, in 1985/86, and tested, in ice, during the spring of 1986. The results of the full scale test programme highlighted correlation problems between the ship's predicted performance, based on the model tests, and the measured full scale performance. This correlation problem existed for both the original bow and the new Melville bow.

One possible explanation for this correlation problem was identified as the model scale representation of the hull surface and the ice/hull interaction, or friction coefficient.

As a result of this work a research project has been completed to review the methods presently used to characterise the hull surface and to conduct a series of model tests to investigate this phenomenon in more detail. The work described in this summary report has been divided into two parts; a literature review of pertinent information, and a model test programme.

2. FRICTION COEFFICIENT REVIEW

The importance of the friction coefficient on the total resistance of an icebreaker has been recognised for several years, this early work represented the friction coefficient as coulomb, independent of contact forces. Coulomb friction may be defined by the relationship:

Tangential Force = (Constant) x Normal Force

The constant in this expression is defined as the coefficient of friction. More recent studies have indicated that the mechanism of the ice/hull interface is more complex and may be more accurately represented by:

Tangential Force = (Constant) x Normal Force + Offset

The constant in this expression is the friction coefficient and the offset is dependent on the surface conditions.

There are many factors that affect the numerical value attributed to the coefficient of friction between the ice and ship's hull. The key variables are:

- equipment used to measure the friction coefficient,
- surface variables including surface roughness and profile,
- ice variables including roughness, surface profile and mechanical properties,
- normal force, and
- speed.

The influence of each of these variables has been studied at model and full scale. The following paragraphs review and discuss each variable and their perceived influence on the friction coefficient at model and full scale.

a) Friction testing equipment

Many different methods have been adopted to measure the friction coefficient including rotating arms, sliding carriages and sledges dragged over the ice. The most recently developed equipment is the load cell installed on the POLARSTERN ice breaking research ship and the PROTECTOR, a small ice breaking tug. This instrumentation has permitted the measurement of friction coefficient directly from the hull surface.

At model scale the friction coefficient may be measured using hull surface samples dragged over the ice or ice samples dragged over the model surface, or a surface identical to the model. There are advantages and disadvantages to both these methods. More recently the commonly accepted method has been to slide a sample panel, that has been treated with the

same material as the model beneath an ice sample. By recording vertical and tangential loads between the ice and the surface, friction coefficient can be deduced.

b) Material surface variables

Many tests have been conducted by experimenters on different surface roughnesses to obtain a correlation between roughness, the Centre Line Average (CLA) value, and the friction coefficient. The results of these tests usually confirm that, as the materials get rougher, the material/ice friction coefficient tends to increase. However, the surface morphology has also been found to be very important and, in some cases, surfaces with the same CLA value have significantly different friction coefficients.

In addition to roughness, the morphology and thermal properties of the interfacing surfaces also affects the friction coefficient.

c) Ice variables

The mechanical and physical characteristics of the ice will effect the friction coefficient with other materials. Unfortunately, the ice characteristics at full scale are rarely defined with any accuracy and usually only a general ice description is given. At model scale, the ice can be defined in more detail and specific trends identified.

The ice variables that have been studied at model scale, to investigate their effect on the friction coefficient, are:

- sample configuration,
- sample size,
- crystal orientation,
- surface morphology, and
- mechanical properties.

The sample configuration has been shown to influence the measured friction coefficient at model scale. Tests of an ice sample on a subject material resulted in significantly different friction values and trends than a sample of material on the ice.

The effect of sample size has also been investigated at model scale and there was no significant variation in friction coefficient was found. During larger sample tests, using a weighted sledge in an ice arena, a larger surface (0.139 to 0.8 m^2) tended to exhibit higher friction coefficients although the tests were irregular and characterised by a "stick and slip" action rather than a smooth slide.

Varying the orientation of the ice sample with the test surface, i.e. ice crystals parallel or perpendicular, have not been shown to produce different friction coefficients.

The influence of the mechanical properties of the model ice on the friction coefficient has been examined by conducting a series of tests using ice samples of different hardnesses.

In the case of an ice sample dragged over a smooth plate, the weaker samples had the highest friction coefficient and were found to be more sensitive to the normal pressure which will act to crush the ice and steel surface together. When the material sample was dragged across ice, the influence of hardness on the friction coefficient was negligible and emphasised the importance of the frictional heat generated in the ice sample causing ice melting at the surface interface.

The surface condition of the sample ice was examined by ten repeated tests of the same ice sample on Inerta and roughened Inerta surfaces. The tests included ice samples oriented with crystals perpendicular and parallel with the test surface. In all cases the calculated friction coefficient did not significantly change from the first test to the last.

d) Normal force

Many experiments have been completed on the effects of normal force on the friction coefficient for samples of ice moving against another material. The relationship between normal force and friction coefficient has most often been expressed as a linear function of frictional shear stress.

Shear Stress = (Constant) x Normal Load + Zero Shear Stress

The zero shear stress is defined by the intercept on the 'y' axis of this linear function. The zero shear stress is associated with the surface interface and has been shown to reduce as the ice hardness increases.

The full scale tests examining the affect of normal force range from sledge tests to instrumented panels on icebreaking ships. The results of these tests indicated that the friction coefficient decreases with normal force to a constant value.

A series of full scale tests on the POLARSTERN icebreaker also indicated that the friction coefficient was strongly dependent on the ship speed. However, the report noted that no analysis of the pressure effects on friction were possible because the actual contact area between the ice and hull was not known.

The POLARSTERN data may be analysed by plotting the tangential force and the normal force. This has been done and results in the linear relationship between the tangential force and normal force with a non zero intercept on the 'y' (tangential force) axis.

This result is similar to model tests results which indicate that as the normal force or pressure increases, the friction coefficient will decrease to a constant value. The value of the zero normal pressure intercept on the 'y' axis is considered to be a function of the ice adhesion to the surface, the type of surface and the ice hardness.

A similar test series was conducted on the Finnish icebreaking salvage tug PROTECTOR. The ship was fitted with two circular load panels, one on the bow and one on the bottom. The front panel experienced considerably higher normal forces than the bottom panel and resulted in lower calculated friction coefficients.

e) Sample Speed

The effect of sample speed on the friction coefficient at full scale has not been resolved. During the full scale tests of the POLAR STAR (Arctec 1982) the radial arm equipment was used to record the friction coefficient as a function of normal force and average speed. It was found that there was no significant trend with average speed.

During the full scale trials of the POLARSTERN, in 1984, the results indicated a different speed relationship for the two instrumented panels on the ships hull. The forward panel did not demonstrate any dependency between friction coefficient and speed and tended to remain constant over the range of zero to 12 knots. The shoulder panel, over the same speed range, showed the friction coefficient increasing linearly with speed. The tests were not able to determine whether this difference in relationship was due to the different normal forces occurring on the two panels or the different ice/hull interaction that was occurring in the two locations.

Model tests investigating the effect of speed on the friction coefficient have been completed for both samples of ice moving on a material and a sample of material moving on ice. In the case of a sample of ice moving on a smooth material the friction coefficient tends to increase with speed. This is believed to be due to the dissipation of the frictional heat. When a smooth material slides over an ice surface, the friction coefficient has been shown to remain constant. This is thought to be due to the constantly changing ice interface with the material and, therefore, there is no time for the ice to melt and the ice/surface interface does not develop the water layer caused by the frictional heat.

Unlike the smooth material, in the case of a rough material sliding over ice, the friction coefficient varies with speed. The reason for this is believed to be due to the penetration of the melt water layer by the material asperities. As the velocity increases, the voids between the asperities tend to fill and the friction coefficient is reduced.

f) Model tests

Although the friction coefficient has been recognised as having a significant effect on the resistance of ships and models, it has not been the subject of any focused series of model test programmes.

Model tests have been conducted on the POLAR class icebreakers at four friction coefficients, 0.01, 0.1, 0.3 and 0.5. The data from the test programme was put into a regression analysis and prediction equations were generated for each hull surface.

The effect of the friction coefficient was shown to be dependent on speed. This was particularly the case for the rough model, which showed a significant reduction discussed above. The smoother models did not demonstrate the same trend and this is compatible with the results of the sample testing in friction coefficient as the speed increased.

Model tests conducted as part of the SS MANHATTAN Arctic marine project (Arctec 1970) concluded that the ice/hull friction was the most dominant component of the resistance and that the resistance of the model was influenced significantly more by the bow than the midbody.

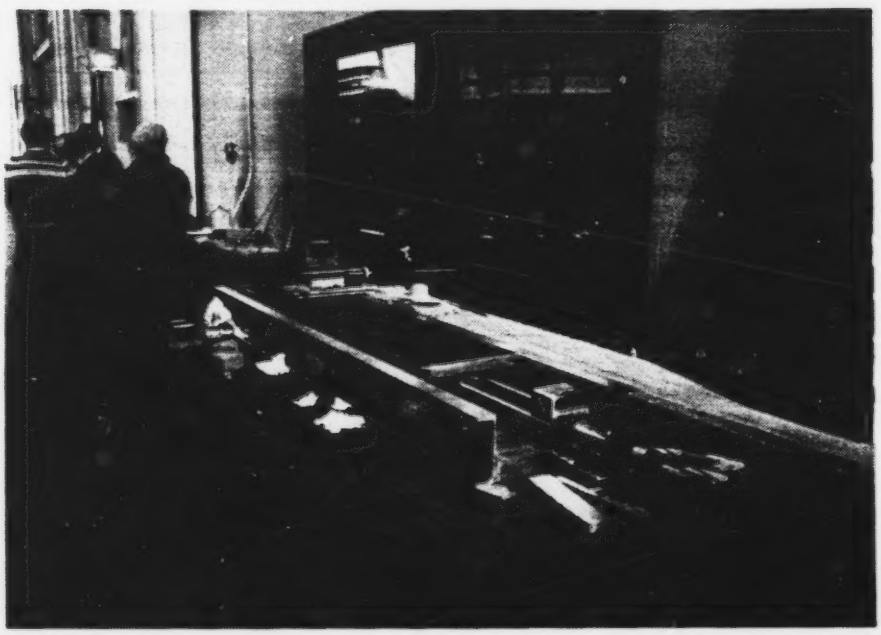
3. SURFACE DEFINITION TESTS

The objective of the model test programme is to investigate the influence of different model surfaces on resistance. This required the development of a number of different paint systems that would produce uniform and consistent surfaces. Each paint system was tested using a sample panel, coated with the specific paint formulation, and a friction jig which was designed and built at IMD. The test equipment and procedure to investigate the different surfaces were selected after a review of existing methods. The final design of the friction jig was developed by IMD with the assistance of Dr. Kitagawa of the Japanese Ship Research Institute, who was resident at IMD during the test period.

The equipment used to measure the friction coefficient of the sample panels is shown in Figure 3.1 and 3.2.

FIGURE 3.1

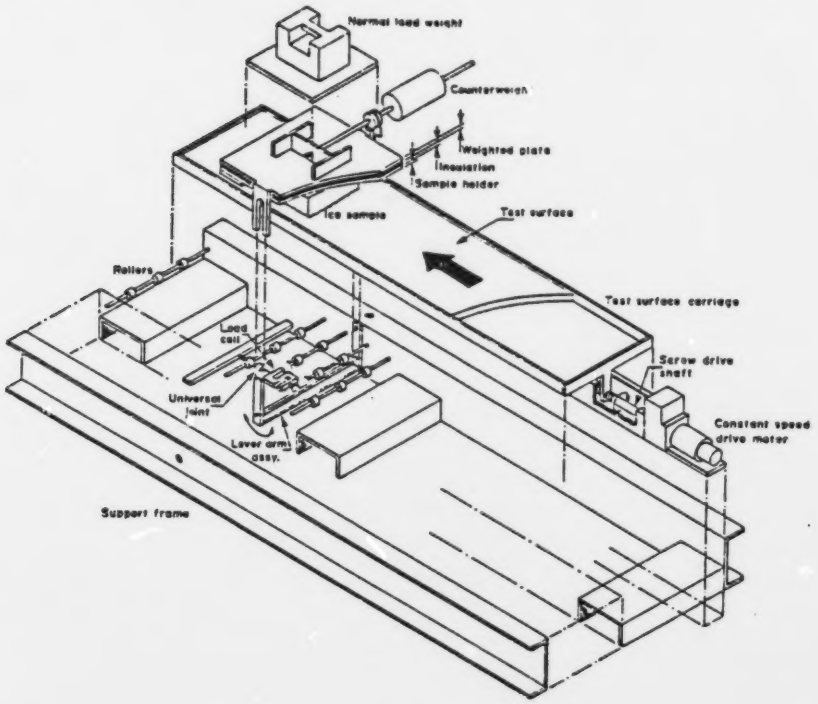
EQUIPMENT USED TO MEASURE FRICTION COEFFICIENT



The test apparatus consisted of a sample holder, onto which the ice sample was attached. This is supported vertically using a fulcrum and counterweight and restrained in the longitudinal direction by a horizontal fulcrum and load cell. The test material is positioned below the ice in a tray that can be driven longitudinally beneath the ice sample by an electric motor and screw drive. The longitudinal motion of the test material is resisted by the loaded ice sample and recorded using the load cell. This longitudinal resistance to motion is considered to be the tangential friction force between the ice sample and material. The equipment is calibrated by suspending standard weights from the ice sample holder and over a pulley at the end of the test jig.

FIGURE 3.2

SCHEMATIC OF FRICTION JIG USED AT IMD



The tangential force from the load cell was displayed on a chart recorder and calibrated to yield tangential force in Newtons.

A number of different sample finishes were investigated, including acrylic lacquers and epoxies.

The majority of the sample friction tests were conducted simultaneously with the model friction tests. In addition, to increase the number of sample test runs, a number of the tests were also conducted in association with other test programmes at IMD.

The range of normal loads on the ice samples were 2, 5, 10, 15 and 20 kg. Nominal pressures on the 0.14 m sample were therefore 1, 2.5, 5, 7.5 and 10 kPa. The sample speed was held constant for all the tests at 25 cm/sec.

Two different surface preparations were used for the test programme. Three lower friction coefficients were created using an epoxy coating called Imron, with a number of additives to modify the surface characteristics. Table 3.1 lists the components of the paint used for each surface finish. An additional high friction coefficient surface was created by laying a coarse fibreglass mat on the surface of the model.

TABLE 3.1

Components of Paint Used for Each Surface Finish

	Surface 1	Surface 2	Surface 3
Imron A	2 quarts	2 quarts	2 quarts
Imron B	1/2 quarts	1/2 quarts	1/2 quarts
magnesium silicate	-	400 gm	400 gm
catalyst	14 gm	14 gm	14 gm
thinner	200 gm	200 gm	200 gm
air gun pressure	50 psi	50 psi	50 psi
flattening agent	-	300 gm	300 gm

From IMD Report Williams 1986

The friction coefficient has been defined by the following relationship;

Tangential Force = Friction Coefficient x Normal Force + Offset

The results from the sample test programme are presented as normal force versus tangential force. The form of this relationship, which is defined by drawing a straight line through the data, yields the offset.

The initial programme was intended to consist of three hull surfaces with a middle friction coefficient of 0.1. Unfortunately the "rough" surface resulted in a friction coefficient of only about 0.06. As a result it was decided to re-test another sample panel and bow section with a significantly rougher surface finish.

Eight model surfaces were tested, represented by five panels, an example of these tests are presented in Figures 3.2 and 3.3. Figure 3.2 shows the normal versus tangential force recorded during the experiment. The form of the data consists of a linear relationship with either a positive or negative offset. The offset appears to vary outside the controlled parameters of these tests and has been attributed to the particular physical and mechanical properties of the ice. These may have varied slightly for each experiment whilst the ice remained within the control parameters of the overall test strength and surface texture criteria. The derivative of the linear equation, representing each set of data for each panel, remains reasonably constant and this supports the form of the friction coefficient equation defined above.

In addition to the presentation of tangential force versus normal force, this type of data may also be presented as friction coefficient versus normal force. An example of this presentation is presented in

FIGURE 3.3

SURFACE - 1
TEST PANEL RESULTS

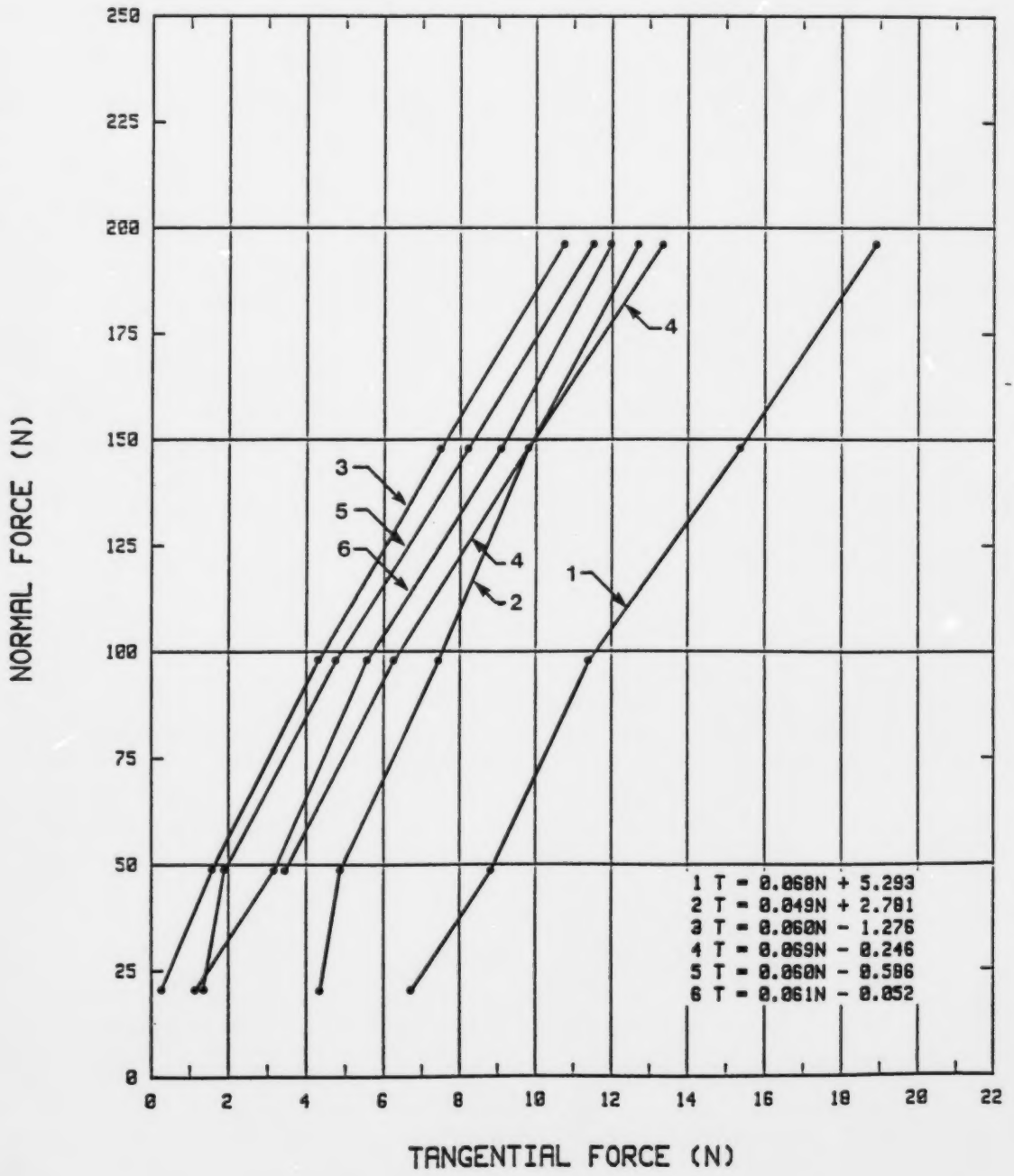


FIGURE 3.4

SURFACE - 1
FRICTION VERSUS NORMAL FORCE

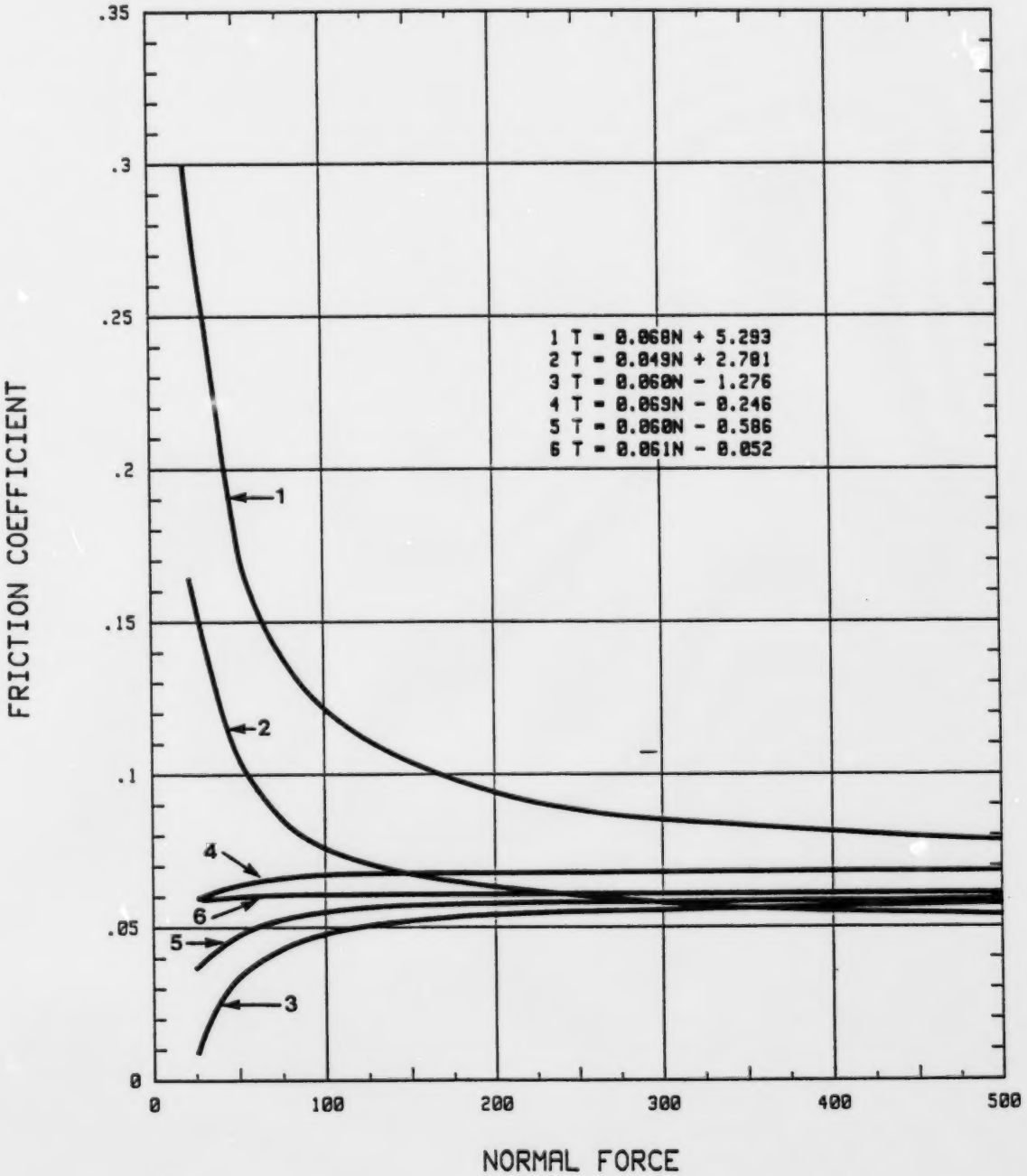


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Figure 3.3. Comparing this data with the experiments by previous researchers confirms that the friction equipment and test procedures are compatible with current research standards.

The friction coefficient for each panel has been obtained by taking the mean of the friction coefficients calculated from each surface. This results in the values shown in Table 3.2. These values have then been attributed to the respective model segment in the following section.

In addition to the calculation of friction coefficient, the test surfaces were also measured with a Taylor-Hobson surtronics profilometer. The results from these tests may be compared with the calculated friction coefficients and this is done in Table 3.2.

TABLE 3.2

RESULTS OF THE FRICTION COEFFICIENT PANEL TESTS

Panel	Number of Tests	Average Friction Coefficient	Standard Deviation
Stern Section	7	.100	.0124
Panel #1,	6	.061	.0072
Panel #2,	3	.004	.0012
Panel #3,	3	.065	-
Panel #4	3	.354	.295

4. MODEL TESTS

The model tests were conducted at the ice tank of the Institute for Marine Dynamics in St. John's, Newfoundland. Details of the ice tank and the facility have been published in the literature. The model consisted of seven parts; three bows, three midbodies and one stern. Each part was prepared with a different surface preparation as described in the previous section.

The model was a 1:30 scale reproduction of the ARCTIC, an Arctic Class, 28,000 tonne DWT OBO carrier. The model tests consisted of 11 towed resistance tests in model EG/AD ice representative of 1.5 m, 570 kPa full scale ice. An additional test was also conducted in an equivalent 1.2 m ice sheet to investigate the effect of ice thickness and to compare with results from previous model tests. These ice thicknesses and strengths correspond to 50 mm and 40 mm, 19 kPa model ice.

Reference will be made throughout this section to surfaces 1 to 4. In all cases surface 1 is the middle roughness surface with a friction coefficient of 0.061. Surface 2 is the very smooth surface with a measured friction coefficient of 004. Surface 3 is the original rough surface which resulted in a similar roughness to the middle roughness and has a nominal friction coefficient of 0.065. Surface 4 is the very rough surface with a friction coefficient of 0.354.

The model test programme may be divided into two parts. The first part was conducted between September 1986 and February 1987 and consisted of the three lower friction coefficients. Following a review of these tests it became apparent that additional tests were required with a rougher friction coefficient. These were conducted in October 1986.

The programme was conducted using standard test procedures presently in force at IMD.

The results of the test programme are presented in Table 4.1. The table is extracted from Melville's standard model test analysis program and presents in the first four columns the ice sheet number, and the measured ice thickness, strength and model speed. The fifth column presents the resistance data. If this has been corrected, then the column will show corrected data. Any correction applied is shown in the sixth column. The seventh column is the ice sheet identifier used in the program. If the same model is run twice then the description may include a prefix, for example 'T' for thinner ice, or '1' and '2' for successive tests. The note column identifies any variations in the standard model test correction procedure and is described at the bottom of each page.

The model test results represent a total of twelve ice sheets and may be presented in a number of combinations. For the purpose of this report the three combinations of hull sections and friction coefficient will be compared against the base case of Surface 1 on the bow and midbody. However the data presented in Table 4.1 does not consist of a single ice strength or thickness and as a result corrections should be made to the data that will normalize each data set.

TABLE 4.1

IMD FRICTION PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
1	49.0	19.0	.190	76.0	0.000	1BOW 1 MIDBODY 1	
2	51.0	19.0	.330	89.0	0.000	1BOW 1 MIDBODY 1	
2	49.0	19.0	.470	103.0	0.000	1BOW 1 MIDBODY 1	
2	49.0	19.0	.610	111.0	0.000	1BOW 1 MIDBODY 1	
3	39.0	17.0	.190	50.0	0.000	TBOW 1 MIDBODY 1	
3	41.0	17.0	.320	63.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	17.0	.460	70.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	17.0	.600	81.0	0.000	TBOW 1 MIDBODY 1	
3	39.0	0.0	.190	20.5	0.000	TBOW 1 MIDBODY 1	
3	41.0	0.0	.320	37.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	0.0	.460	41.0	0.000	TBOW 1 MIDBODY 1	
3	40.0	0.0	.600	43.0	0.000	TBOW 1 MIDBODY 1	
4	49.0	19.0	.180	46.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.320	59.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.460	76.0	0.000	BOW 2 MIDBODY 1	
4	50.0	19.0	.600	88.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.190	20.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.320	24.0	0.000	BOW 2 MIDBODY 1	
4	50.0	0.0	.600	36.0	0.000	BOW 2 MIDBODY 1	
5	48.0	16.0	.190	56.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.330	74.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.470	86.0	0.000	BOW 3 MIDBODY 1	
5	49.0	16.0	.600	103.0	0.000	BOW 3 MIDBODY 1	
5	49.0	0.0	.330	34.0	0.000	BOW 3 MIDBODY 1	
5	49.0	0.0	.600	53.0	0.000	BOW 3 MIDBODY 1	
6	48.0	19.0	.190	39.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.330	45.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.470	57.0	0.000	BOW 2 MIDBODY 2	
6	48.0	19.0	.600	60.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.190	15.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.330	21.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.470	25.0	0.000	BOW 2 MIDBODY 2	
6	48.0	0.0	.600	31.0	0.000	BOW 2 MIDBODY 2	
7	48.0	17.0	.190	66.0	0.000	BOW 3 MIDBODY 2	
7	50.0	17.0	.330	78.0	0.000	BOW 3 MIDBODY 2	

\# = Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.1 CON'T

[illegible] PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
7	49.0	17.0	.470	92.0	0.000	BOW 3 MIDBODY 2	
7	50.0	17.0	.600	101.0	0.000	BOW 3 MIDBODY 2	
7	48.0	0.0	.190	29.0	0.000	BOW 3 MIDBODY 2	
7	50.0	0.0	.330	37.0	0.000	BOW 3 MIDBODY 2	
7	49.0	0.0	.470	46.0	0.000	BOW 3 MIDBODY 2	
7	50.0	0.0	.600	55.0	0.000	BOW 3 MIDBODY 2	
8	48.0	19.0	.190	74.0	0.000	BOW 1 MIDBODY 2	
8	50.0	19.0	.330	93.0	0.000	BOW 1 MIDBODY 2	
8	48.0	19.0	.470	98.0	0.000	BOW 1 MIDBODY 2	
8	50.0	19.0	.600	119.0	0.000	BOW 1 MIDBODY 2	
8	48.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 2	
8	50.0	0.0	.330	42.0	0.000	BOW 1 MIDBODY 2	
8	48.0	0.0	.470	48.0	0.000	BOW 1 MIDBODY 2	
8	50.0	0.0	.600	58.0	0.000	BOW 1 MIDBODY 2	
9	48.0	23.0	.190	65.0	0.000	BOW 3 MIDBODY 3	
9	50.0	23.0	.330	86.0	0.000	BOW 3 MIDBODY 3	
9	49.0	23.0	.470	97.0	0.000	BOW 3 MIDBODY 3	
9	50.0	23.0	.600	124.0	0.000	BOW 3 MIDBODY 3	
9	48.0	0.0	.190	26.0	0.000	BOW 3 MIDBODY 3	
9	50.0	0.0	.330	38.0	0.000	BOW 3 MIDBODY 3	
9	49.0	0.0	.470	45.0	0.000	BOW 3 MIDBODY 3	
9	50.0	0.0	.600	51.0	0.000	BOW 3 MIDBODY 3	
10	51.0	18.0	.190	51.0	0.000	BOW 2 MIDBODY 3	
10	54.0	18.0	.330	65.0	0.000	BOW 2 MIDBODY 3	
10	52.0	18.0	.470	78.0	0.000	BOW 2 MIDBODY 3	
10	53.0	18.0	.600	89.0	0.000	BOW 2 MIDBODY 3	
10	51.0	0.0	.190	23.0	0.000	BOW 2 MIDBODY 3	
10	54.0	0.0	.330	31.0	0.000	BOW 2 MIDBODY 3	
10	52.0	0.0	.470	40.0	0.000	BOW 2 MIDBODY 3	
10	53.0	0.0	.600	43.0	0.000	BOW 2 MIDBODY 3	
11	46.0	21.0	.190	77.0	0.000	BOW 1 MIDBODY 3	
11	48.0	21.0	.330	84.0	0.000	BOW 1 MIDBODY 3	
11	47.0	21.0	.600	109.0	0.000	BOW 1 MIDBODY 3	
11	46.0	0.0	.190	29.0	0.000	BOW 1 MIDBODY 3	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.1 CON'T

IMD FRICTION PROGRAM
UNCORRECTED TEST RESULTS

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
11	48.0	0.0	.330	49.0	0.000	BOW 1 MIDBODY 3	
11	47.0	0.0	.600	78.0	0.000	BOW 1 MIDBODY 3	
12	49.0	20.0	.190	58.0	0.000	280W 1 MIDBODY 1	
12	50.0	20.0	.330	81.9	0.000	280W 1 MIDBODY 1	
12	48.0	20.0	.470	83.6	0.000	280W 1 MIDBODY 1	
12	50.0	20.0	.610	126.0	0.000	280W 1 MIDBODY 1	
12	49.0	0.0	.190	25.2	0.000	280W 1 MIDBODY 1	
12	50.0	0.0	.330	28.5	0.000	280W 1 MIDBODY 1	
12	48.0	0.0	.470	41.3	0.000	280W 1 MIDBODY 1	
12	50.0	0.0	.610	52.5	0.000	280W 1 MIDBODY 1	
13	47.0	20.0	.190	114.6	0.000	BOW 4 MIDBODY 1	
13	49.0	20.0	.330	122.9	0.000	BOW 4 MIDBODY 1	
13	49.0	20.0	.470	148.7	0.000	BOW 4 MIDBODY 1	
13	50.0	20.0	.610	198.3	0.000	BOW 4 MIDBODY 1	
13	47.0	0.0	.190	49.9	0.000	BOW 4 MIDBODY 1	
13	49.0	0.0	.330	70.9	0.000	BOW 4 MIDBODY 1	
13	49.0	0.0	.470	76.6	0.000	BOW 4 MIDBODY 1	
13	50.0	0.0	.610	96.4	0.000	BOW 4 MIDBODY 1	

= Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

A review of Table 4.1 shows that the target ice strength and ice thicknesses were achieved with a high level of consistency. The ice crushing and shear strengths were not measured extensively and this is normal for current model testing.

The model tests were all conducted with target ice thicknesses and strengths, however, as with any physical testing, the target values were not always obtained. As a result some minor adjustments or normalisations are necessary to ensure that when the data is analysed for variations in friction coefficient the comparison is independent of ice thickness and strength considerations.

The validity of these procedures, to normalise the resistance for variations in strength and thickness, may be assessed by comparing the two identical tests conducted on the ARCTIC model with a friction coefficient of 0.06. Table 4.2 is a comparison between the normalised resistances of the two identical tests using a number of different methods to correct the measured data to target values. The first three columns of the table present the raw, uncorrected data at the four test speeds, for test 1 (September 1986) and test two (October 1987). The next two sets of three columns present the resultant corrected data from two variable group corrections. The first two columns of each set are the corrected resistance and the third column is the percentage difference between the two tests. The fourth set of three columns presents the same data for the correction technique using presawn ice tests and/or other ice sheets to develop resistance versus ice strength and resistance versus ice thickness relationships. Based on the comparison between the two identical model tests, the normalisation based on using an ice sheet of a different thickness and the presawn tests appear to result in the closest correlation, however it may be noted that the variable group of thickness to the power 1.2, and strength to the power 0.4 results in a very similar level of correlation.

TABLE 4.2

COMPARISON OF CORRECTED RESISTANCE DATA USING THREE DIFFERENT METHODS

Raw model test data			Variable Group $R/\sigma^{0.4} * h^{1.2}$			Variable Group $\sigma * h^2$			Data Corrected with Additional Ice Sheets		
Speed (m/sec)	Resistance (N)		Corrected Resistance (N)		Percentage Difference	Corrected Resistance (N)		Percentage Difference	Corrected Resistance (N)		Percentage Difference
	Test 1	Test 2	Test 1	Test 2		Test 1	Test 2		Test 1	Test 2	
0.19	76	58	77.9	58.2	34.0	79.1	57.4	37.8	79	58	34.8
0.33	89	82	86.9	80.2	8.4	85.5	77.8	9.9	86	80	9.1
0.47	103	84	105.5	86.0	22.7	107.2	86.2	24.4	107	87	22.1
0.61	111	126	113.7	123.4	7.9	115.6	119.7	3.4	114	122	-6.5

Based on this result it was elected to normalize all the data using the results from the two ice sheets with different thicknesses for the thickness correction and the presawn tests for the strength correction. The data used in the subsequent analysis is presented in Table 4.3 at target strength and thickness values.

The variation of resistance with friction coefficient has been analysed by comparing each combination of friction coefficient with the middle coefficient on the bow and midbody.

Results of the model test series are presented in Figures 4.1, 4.2 and 4.3.

TABLE 4.3

FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
1	49.0	19.0	.190	78.6	2.600	IBOW 1 MIDBODY 1	
1	51.0	19.0	.330	86.4	-2.300	IBOW 1 MIDBODY 1	
1	49.0	19.0	.470	106.7	3.667	IBOW 1 MIDBODY 1	
1	49.0	19.0	.610	114.3	3.333	IBOW 1 MIDBODY 1	
2	39.0	17.0	.190	56.1	6.071	TBOW 1 MIDBODY 1	
2	41.0	17.0	.320	63.5	.459	TBOW 1 MIDBODY 1	
2	40.0	17.0	.460	73.4	3.412	TBOW 1 MIDBODY 1	
2	40.0	17.0	.600	85.5	4.471	TBOW 1 MIDBODY 1	
2	39.0	0.0	.190	20.5	0.000	TBOW 1 MIDBODY 1	
2	41.0	0.0	.320	37.0	0.000	TBOW 1 MIDBODY 1	
2	40.0	0.0	.460	41.0	0.000	TBOW 1 MIDBODY 1	
2	40.0	0.0	.600	43.0	0.000	TBOW 1 MIDBODY 1	
3	49.0	19.0	.180	47.6	1.374	BOW 2 MIDBODY 1	
3	50.0	19.0	.320	59.3	0.000	BOW 2 MIDBODY 1	
3	50.0	19.0	.460	76.0	0.000	BOW 2 MIDBODY 1	
3	50.0	19.0	.600	88.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.190	20.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.320	24.0	0.000	BOW 2 MIDBODY 1	
3	50.0	0.0	.600	36.0	0.000	BOW 2 MIDBODY 1	
4	48.0	16.0	.190	65.5	9.507	BOW 3 MIDBODY 1	‡.33
4	49.0	16.0	.330	83.7	9.662	BOW 3 MIDBODY 1	
4	49.0	16.0	.470	97.8	11.778	BOW 3 MIDBODY 1	‡.33
4	49.0	16.0	.600	115.5	12.468	BOW 3 MIDBODY 1	
4	49.0	0.0	.330	34.0	0.000	BOW 3 MIDBODY 1	
4	49.0	0.0	.600	53.0	0.000	BOW 3 MIDBODY 1	
5	48.0	19.0	.190	41.7	2.668	BOW 2 MIDBODY 2	
5	48.0	19.0	.330	47.6	2.629	BOW 2 MIDBODY 2	
5	48.0	19.0	.470	61.1	4.058	BOW 2 MIDBODY 2	
5	48.0	19.0	.600	63.6	3.604	BOW 2 MIDBODY 2	
5	48.0	0.0	.190	15.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.330	21.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.470	25.0	0.000	BOW 2 MIDBODY 2	
5	48.0	0.0	.600	31.0	0.000	BOW 2 MIDBODY 2	
6	48.0	17.0	.190	74.9	8.869	BOW 3 MIDBODY 2	
6	50.0	17.0	.330	82.8	4.824	BOW 3 MIDBODY 2	

‡ = Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.3 CON'T

FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST ‡	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
6	49.0	17.0	.470	100.7	8.687	BOW 3 MIDBODY 2	
6	50.0	17.0	.600	106.4	5.412	BOW 3 MIDBODY 2	
6	48.0	0.0	.190	29.0	0.000	BOW 3 MIDBODY 2	
6	50.0	0.0	.330	37.0	0.000	BOW 3 MIDBODY 2	
6	49.0	0.0	.470	46.0	0.000	BOW 3 MIDBODY 2	
6	50.0	0.0	.600	55.0	0.000	BOW 3 MIDBODY 2	
7	48.0	19.0	.190	79.1	5.063	BOW 1 MIDBODY 2	
7	50.0	19.0	.330	93.0	0.000	BOW 1 MIDBODY 2	
7	48.0	19.0	.470	105.0	6.977	BOW 1 MIDBODY 2	
7	50.0	19.0	.600	119.0	0.000	BOW 1 MIDBODY 2	
7	48.0	0.0	.190	29.0	0.000	BOW 1 MIDBODY 2	
7	50.0	0.0	.330	42.0	0.000	BOW 1 MIDBODY 2	
7	48.0	0.0	.470	48.0	0.000	BOW 1 MIDBODY 2	
7	50.0	0.0	.600	58.0	0.000	BOW 1 MIDBODY 2	
8	48.0	23.0	.190	62.7	-2.335	BOW 3 MIDBODY 3	
8	50.0	23.0	.330	77.7	-8.348	BOW 3 MIDBODY 3	
8	49.0	23.0	.470	91.4	-5.590	BOW 3 MIDBODY 3	
8	50.0	23.0	.600	111.3	-12.696	BOW 3 MIDBODY 3	
8	48.0	0.0	.190	26.0	0.000	BOW 3 MIDBODY 3	
8	50.0	0.0	.330	38.0	0.000	BOW 3 MIDBODY 3	
8	49.0	0.0	.470	45.0	0.000	BOW 3 MIDBODY 3	
8	50.0	0.0	.600	51.0	0.000	BOW 3 MIDBODY 3	
9	51.0	18.0	.190	50.8	-.189	BOW 2 MIDBODY 3	
9	54.0	18.0	.330	58.3	-5.707	BOW 2 MIDBODY 3	
9	52.0	18.0	.470	74.6	-3.442	BOW 2 MIDBODY 3	
9	53.0	18.0	.600	83.5	-5.462	BOW 2 MIDBODY 3	
9	51.0	0.0	.190	23.0	0.000	BOW 2 MIDBODY 3	
9	54.0	0.0	.330	31.0	0.000	BOW 2 MIDBODY 3	
9	52.0	0.0	.470	40.0	0.000	BOW 2 MIDBODY 3	
9	53.0	0.0	.600	43.0	0.000	BOW 2 MIDBODY 3	
10	46.0	21.0	.190	82.9	5.870	BOW 1 MIDBODY 3	
10	48.0	21.0	.330	85.6	1.575	BOW 1 MIDBODY 3	
10	47.0	21.0	.600	115.9	6.867	BOW 1 MIDBODY 3	
10	46.0	0.0	.190	28.0	0.000	BOW 1 MIDBODY 3	

‡ = Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

TABLE 4.3 CON'T

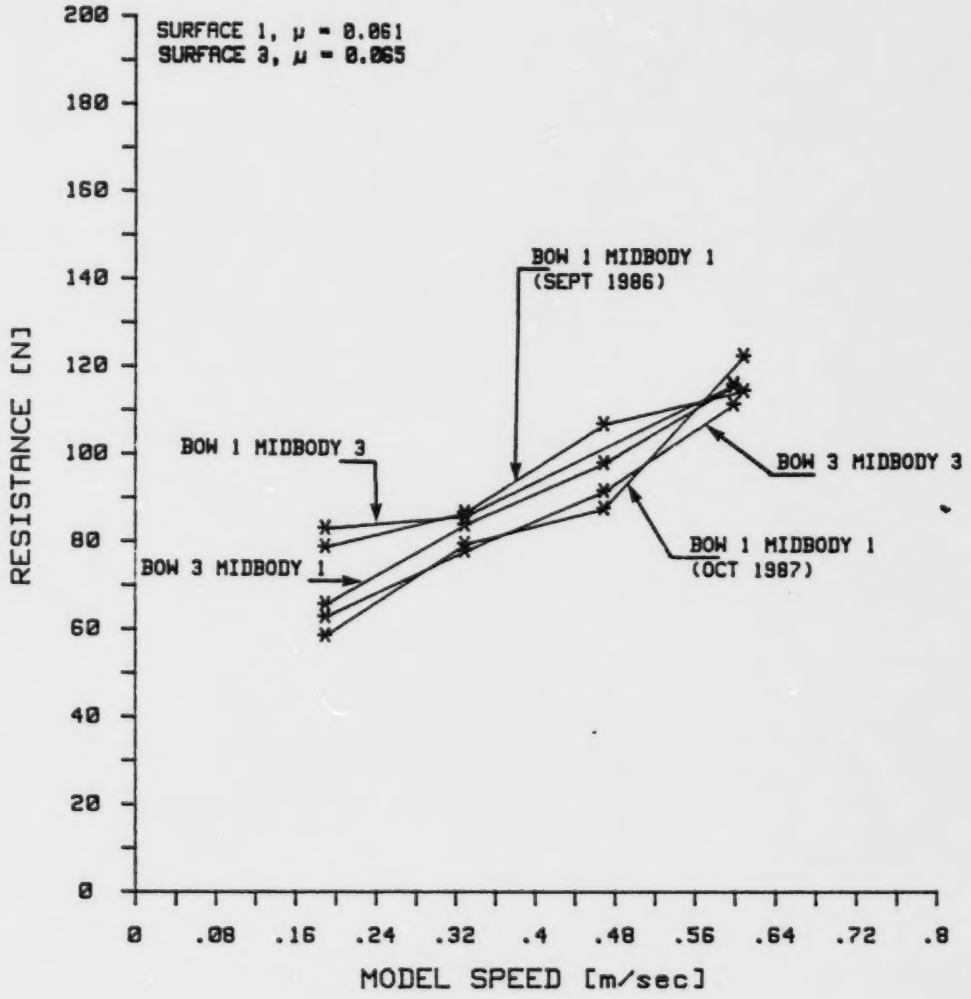
FRICTION PROGRAM
DATA CORRECTED TO TARGET
THICKNESS AND STRENGTH

TEST #	ICE THICK [mm]	FLEXURAL STRENGTH [kPa]	SPEED [m/s]	RESISTANCE OR THRUST [N]	NON-DIM VALUE OR CORR.	TEST DESCRIPTION	NOTE
10	48.0	0.0	.330	49.0	0.000	BOW 1 MIDBODY 3	
10	47.0	0.0	.600	78.0	0.000	BOW 1 MIDBODY 3	
11	49.0	20.0	.190	58.3	.344	280W 1 MIDBODY 1	
11	50.0	20.0	.330	79.2	-2.670	280W 1 MIDBODY 1	
11	48.0	20.0	.470	87.4	3.837	280W 1 MIDBODY 1	
11	50.0	20.0	.610	122.3	-3.675	280W 1 MIDBODY 1	
11	49.0	0.0	.190	25.2	0.000	280W 1 MIDBODY 1	
11	50.0	0.0	.330	28.5	0.000	280W 1 MIDBODY 1	
11	48.0	0.0	.470	41.3	0.000	280W 1 MIDBODY 1	
11	50.0	0.0	.610	52.5	0.000	280W 1 MIDBODY 1	
12	47.0	20.0	.190	123.1	8.527	BOW 4 MIDBODY 1	
12	49.0	20.0	.330	123.9	.990	BOW 4 MIDBODY 1	
12	48.0	20.0	.470	150.4	1.689	BOW 4 MIDBODY 1	
12	50.0	20.0	.610	193.2	-5.095	BOW 4 MIDBODY 1	
12	47.0	0.0	.190	49.3	0.000	BOW 4 MIDBODY 1	
12	49.0	0.0	.330	70.9	0.000	BOW 4 MIDBODY 1	
12	49.0	0.0	.470	76.6	0.000	BOW 4 MIDBODY 1	
12	50.0	0.0	.610	96.4	0.000	BOW 4 MIDBODY 1	

‡ = Data corrected with alternative zero strength data
from the same test set, at the defined speed
% = Data corrected with test defined by the number
preceeding %, followed by test speed
Target thicknesses = 50 and 40 mm
Target strength = 19 kPa

FIGURE 4.1

IMD FRICTION PROGRAM COMPARISON BETWEEN MIDDLE AND FIRST ROUGH SURFACE



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .061 and .065

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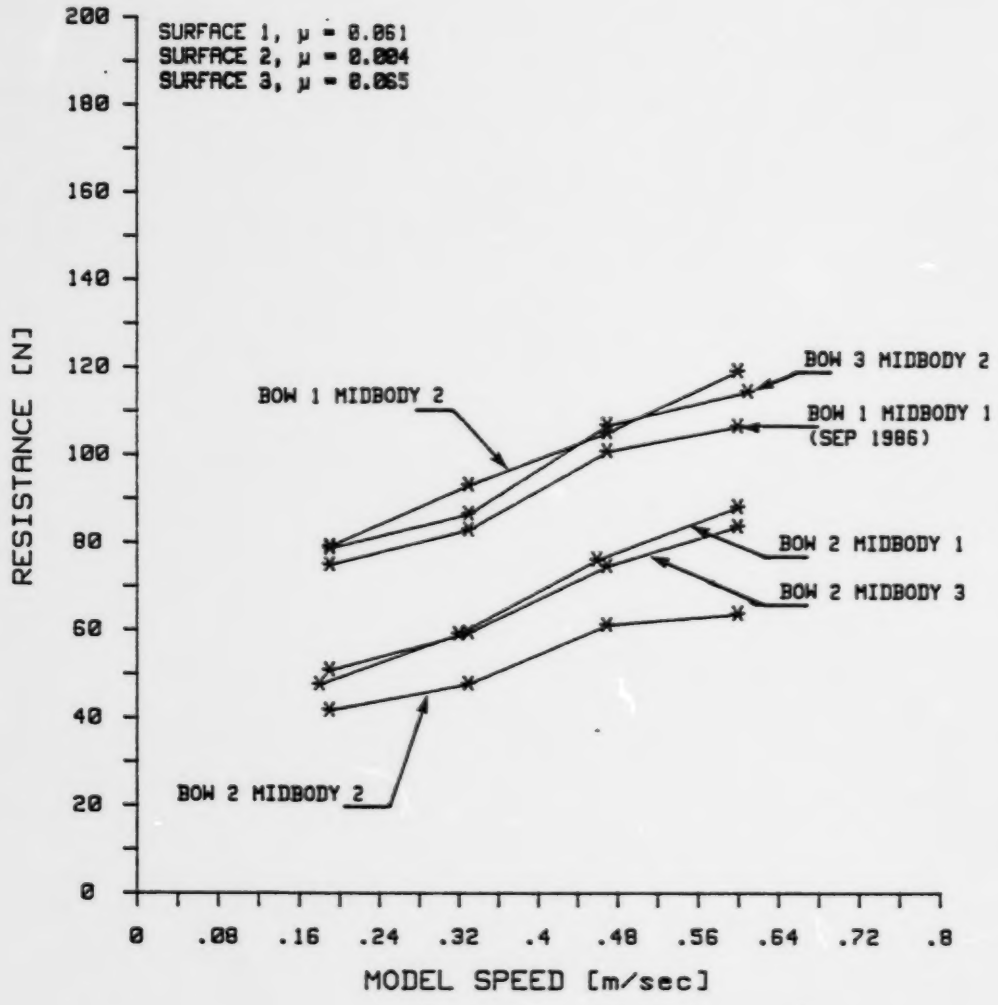
FIGURE 4.2

COMPARISON BETWEEN FRICTION COEFFICIENTS ON THE ARCTIC BOW AND MIDBODY



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .004 .061 and .065

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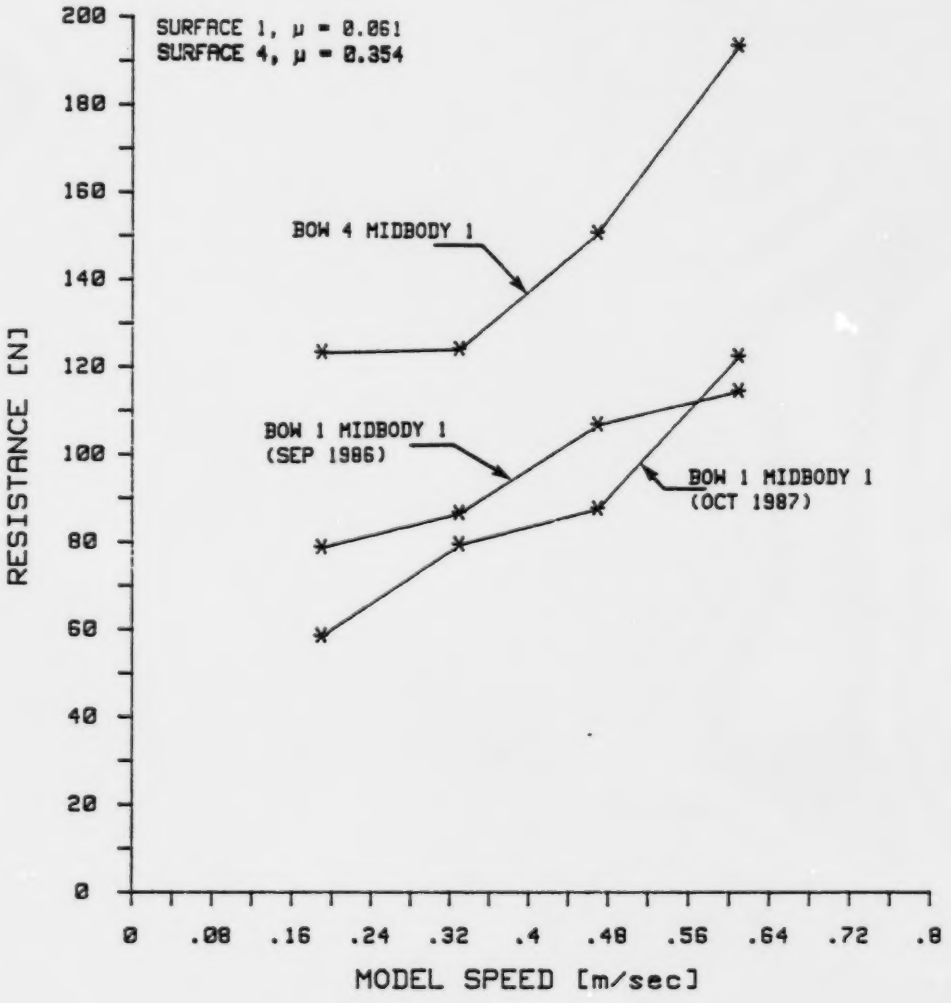
FIGURE 4.3

COMPARISON BETWEEN FRICTION COEFFICIENTS ON THE ARCTIC BOW AND MIDBODY



Target Strength = 19 kPa
Target Thickness = 50 mm
Friction coef. = .354 and .061

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5. CORRELATION ANALYSIS

The ARCTIC model that has been used during these tests was also used during three other test programmes in Canada and Europe. In addition, full scale results have now been made available from the trials of the ARCTIC during 1986. In order to compare the result from the IMD model tests with these other tests it has been elected to compare the model test values at model scale and then convert the data to full scale for comparison with the full scale trial results.

The model of the ARCTIC has been tested at the HSVA facility in Hamburg, the WARC facility in Helsinki, and Arctec Canada Ltd. in Ottawa. The details of these tests have been reported. The comparison between the tanks will be based on resistance values since these were the form of the tests in IMD. The tests in HSVA were only self propulsion, and these have been converted to resistance values by calculating the nozzle thrust (which was not measured during the HSVA tests) and assuming an open water thrust deduction. The details and discussion of the assumptions have been published in the original test report. Although the WARC results were multiplied by conversion factors for the final prediction, the data presented here is based on the corrected measured resistance before any conversion and correlated to the measured friction coefficient. Figure 5.1 presents the data on log-log axis, for a speed of 0.2 m/sec. Although there does appear to be some consistency with the IMD data the remaining data from the other model tanks does not conform in a similar way and underlines the need to ensure consistent testing procedures and techniques.

The results of the data may also be compared with the full scale data. The IMD model tests were only conducted in the resistance mode and as a result the data from these tests are modified to required thrust by using the open water thrust deduction fraction. The comparison is shown in Figure 5.2.

Figure 5.2 represents the ship speed against ice thickness for all the model tests and the full scale performance of the Arctic. The results presented from each of the tanks is the full scale prediction of the model using their own prediction technique. For example the WARC data includes the 1.29 friction correction factor. The scatter of data is predictable and, as observed after the full scale trials, the HSVA prediction was the closest to the tested performance. It can be seen from this figure that, at a scale of 1:30 and in 50 mm ice, the IMD tank appears to predict the performance of the Arctic when the model has a friction coefficient of about 0.06. In thinner ice the same friction coefficient does not conform with the full scale or model scale trends of speed versus ice thickness. The reason for this is unclear but should be examined further with additional model tests at the thinner ice thickness.

FIGURE 5.1

RESISTANCE VERSUS LOG FRICTION COEFFICIENT

FOR HSVA, WARC, ACL AND IMD

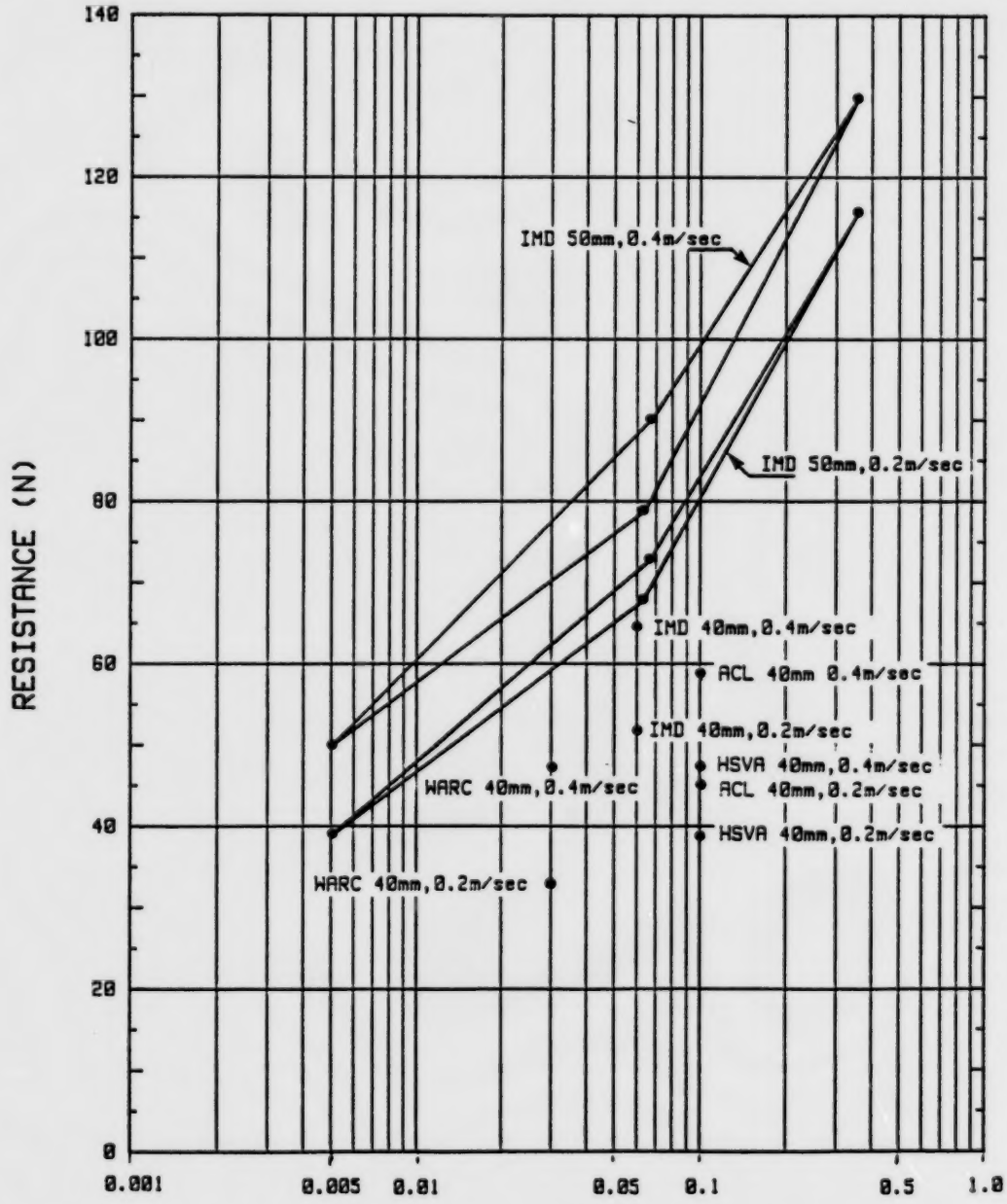

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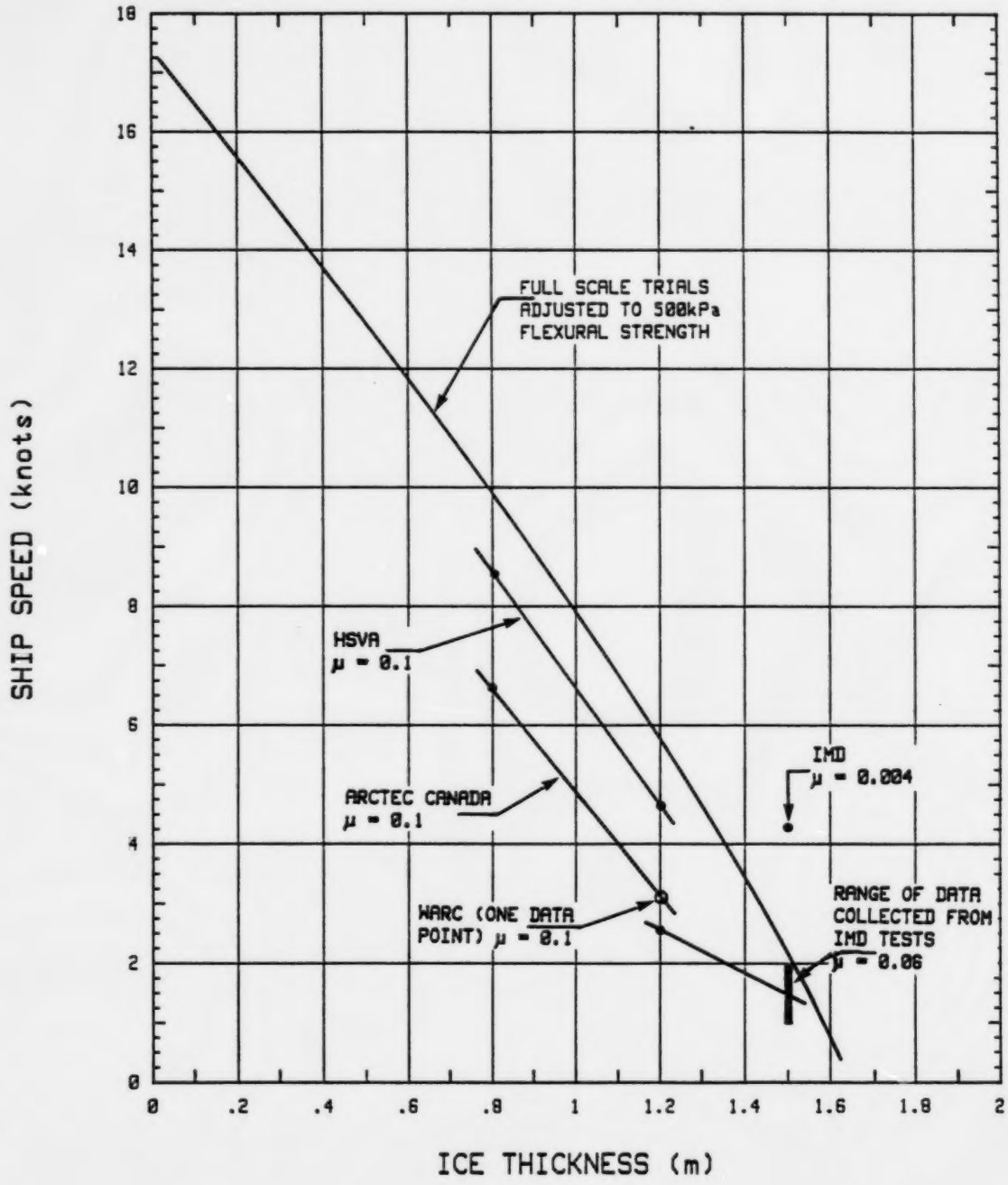
FIGURE 5.2

MV ARCTIC - SPEED VERSUS ICE THICKNESS
COMPARISON OF MODEL AND FULL SCALE RESULTS



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6. CONCLUSIONS

The conclusions of this model test programme may be summarised as follows;

a) A review of the literature highlights the significance of the friction coefficient. Model and full scale tests have shown that the coefficient is dependent on the normal force, the type and roughness of the hull surface and the type and condition of the ice surface. Although it has been shown that rougher surfaces, of the same type, result in higher friction coefficients dissimilar surface types may reverse this trend and result in smoother surfaces having higher friction coefficients. Clearly the testing methodology and conditions of the test are of paramount importance both for full scale and model scale tests.

b) The surface definition tests conducted with the friction jig resulted in test results compatible with those recorded by previous researchers.

c) The model tests of the friction coefficient were conducted at IMD over a period of a year. A repeated test from one test period did not conform well to the same test conducted a year later and although this is a significant period of time it does indicate that the ice mechanical properties may have changed although the standard measuring techniques did not recognise any difference between the ice sheets.

d) The first rough surface tested as part of the September 1986 tests were not distinguishable from the middle surface and resulted in a second rough surface, which was tested in October 1987.

e) The influence of the friction coefficient is significantly stronger at the bow, than on the midbody. The tests have shown that the influence of varying the friction coefficient on the midbody is negligible compared to increasing the friction coefficient on the bow. A reduction in the friction coefficient on the bow from 0.06 to 0.004 resulted in a 45% reduction in resistance.

f) The results of the IMD test programme indicate a different ice thickness dependence than any other tank, and full scale.

g) The test data recorded for a friction coefficient of 0.061, the middle surface, correlated very closely to the full scale performance of the Arctic.

h) Subsequent tests of the same model in ice sheets with measurably identical ice properties resulted in significant variations in the resistance. This variation is considered to be due to different ice mechanical properties that were not recorded during the test, such as crushing or shear strength.

7. RECOMMENDATIONS

As with any research project, the information gathered during the tests identifies areas that require further work. These may be summarised as;

1. Additional thinner ice sheets should be tested to clarify the apparent lower dependency of resistance on ice thickness, shown during the IMD tests.

2. Additional work should be done to test the new rough surface on the midbody of the ARCTIC to confirm the low influence of midbody friction on resistance at this higher friction coefficient.

3. The mechanical properties of the ice are believed to be responsible for the non conformity between two identical tests. Additional work should be done to establish a better method to measure the properties of an ice sheet more thoroughly. An instrument called the INDEXER is currently under development by Melville, IMD and TDC that will be capable of monitoring the flexural, shear and crushing strength of the model ice.

4. The current tests have been undertaken with one type of bow. To confirm whether this relationship is bow form dependent another set of tests should be conducted on a second type of bow form. The recent, unpublished, results of the R-Class tests in a number of different tanks should be reviewed to asses the value of this work.

5. Additional lower speed tests should be run to investigate the very low speed effect of friction, identified during full scale trials by Makinen.

6. Additional friction tests should be conducted on the test panels using higher normal forces, or smaller test samples. Preparation for this work is currently under way at IMD where structural modifications are being made to the friction jig to support higher normal loads.

7. Additional friction tests should be conducted on the test panels using different orientations of ice/surface interface. Tests should also be conducted to validate the quadratic equation form of the friction coefficient definition. These should include tests with 'standard' surfaces to calibrate the equipment and develop relationships between the surface morphology and friction coefficient.

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